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Cost modelling study on the feasibility of on-orbit refuelling of Indian Geo-satellite fleet

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Abstract—**With the increasing demand for geostationary satellites services, all efforts are being made to minimize the cost of the entire geo-satellite system. On-orbit refuelling of geo-satellites is one of the ways to achieve this. In this regard a geo-refuelling system utilising multiple refueller satellites for on-orbit refuelling using current capabilities of satellites and launchers of ISRO is configured. For this initially an economic feasibility study was carried out based on unit telecommunication cost of refuelled and conventional geo satellites. The study was able to identify the main parameters of a regularly refuelled geo-satellite fleet which dictate its economic feasibility. For a geo-satellite fleet with refuelling, various fleet combinations are possible with the four different categories of satellites viz, I1k, I2k, I3k, I4k and with multiple refuellers. All such possible combinations of refuellers and refuelled satellites are explored and combinations which provide desirable profitability are narrowed down for further selection. Two notional mission scenarios are identified and suitable satellite categories and combinations for each scenario is identified which provide economic viability.**

Index Terms—**Geo-refuelling , cost-benefit analysis , Geostationary satellites , Satellite Configuration**

I. INTRODUCTION

Geostationary satellites are one of the most widely used systems devised which are meant to be operational for at least 15 years without any servicing. The prospect of on-orbit servicing of these satellites opens a wide area for improvement in satellite payload capacity and operational life.

Different servicing paradigms exists for geostationary satellites. One is where a servicer satellite is docked to a target satellite and the servicer takes over its station keeping operations, thus extending the life of the target satellite. Another one is when a servicer satellite replenishes the propellants of multiple target satellites. The latter provides better profitability as the amount of on-orbit payload which is being revitalised is more. However, refuelling is yet to be demonstrated in geostationary orbit. In February-2020, the first docking in geo orbit was done by the Mission Extension Vehicle-1 of Northrop Grumman, which uses the first servicing paradigm [1]. The SMART OLEV platform is also employing the first paradigm [2].

With current trend of increased utilisation of geo-satellites for broadband applications, maintaining a cost-effective fleet of geo-satellites is crucial. In order to reduce the cost further, a study was carried out on a geo-satellite refuelling system and a servicer (refueller) satellite was configured utilising the current capabilities of Indian Space Research Organisation. As a precursor for this an economic feasibility study was performed. The main objective of this study was to investigate the current economic feasibility of maintaining a regularly refuelled geo-satellite fleet and to identify key system parameters.

II. BASIC CONSTRAINTS

In order to reduce the overall cost and for operational ease it is considered that all refueller satellites are launched from Indian launchers. Thus, in order to carry the maximum propellant to geosynchronous orbit GSLV MKIII is considered as the launcher with the maximum payload capacity of 4500kg. The launcher will be injecting the refueller satellites to a standard geosynchronous transfer orbit with perigee of ≈170km and apogee of ≈35786km with an inclination of ≈21deg. The limit on maximum lift-off mass is the main design constraint for the technical and economic feasibility of the whole geo-satellite refuelling system.

A. Refuelling Strategy

A refueller satellite is placed in a geostationary parking orbit 100km above the geostationary orbit with Indian ground station visibility. Few orbiting geo satellites with low fuel is selected for refuelling and are referred as target satellites. The refueller is then configured to visit all the target satellites with a fuel demand, this visit is being referred as a refuelling run. Propellant load for a predetermined operational life is provided to each of the target satellites in a refuelling run. After refuelling the refueller is returned back to parking orbit. This is continued until the refueller is left with propellant needed for its transfer to graveyard orbit. Two notional mission scenarios are discussed which are based on different strategies for refuelling run.

III. COST MODELLING FOR GEO-REFUELLING

Before configuring the refueler satellite it is imperative that the economic feasibility and achievable profitability are studied and understood. The system constraints can then be identified and care can be taken during the configuration

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phase. Reference [3] proposed a simple model based on the unit telecommunication cost, that is the cost for placing and maintaining one kilogram of communication payload at geosynchronous orbit for one year. He essentially discusses the refuelling aspects with a single refueller. This simple model can be modified for studying the economic feasibility and identifying the sensitive parameters of the refuelling system with multiple refuellers and with multiple refuelling runs. The empirical costing parameters in the model have changed with time [4], and hence those were updated to suit the Indian scenario. The total cost and profitability of the refuelling system is given by (1) to (4).

$$C_{sat.tot} = C_{sat} + C_L + C_{ops} + C_{ser} \tag{1}$$

where C_{sat} is the Satellite cost (production, testing and management), C_L is the Launch cost of GSLV MKIII, C_{ops} is the Operational cost, C_{ser} is the Extra cost for refuelling one satellite and $C_{sat.tot}$ is the Overall cost per communication satellite.

When there are n target satellites to be refuelled with m refuellers,

$$C_{ser} = \frac{m}{n}\left(C^R_{sat} + C^R_L + C^R_{ops}\right) \tag{2}$$

where, C^R is the cost values for a refueller.

The unit telecommunications cost (c) of a regularly refuelled satellite (target satellite) is given by,

$$c = \frac{C_{sat.tot}}{M_p L} \tag{3}$$

where L is the operational life of a target satellite and M_p is the Payload mass of a target satellite.

Relative Profitability (P_{rel}) of a target satellite will give the relative cost advantage against when the same payload mass is placed on a conventional satellite for the same lifetime as a target satellite. And the equation for P_{rel} is given by,

$$P_{rel} = \frac{(c^* - c)M_p L}{C_{sat.tot}} = \frac{c^* - c}{c} \tag{4}$$

where c^* is the unit telecommunication cost without refuelling.

The study uses the current capabilities of geostationary satellites of ISRO and looked at how the capabilities can be augmented to achieve better system performance by on-orbit refuelling. Here a satellite with conventional bi-propellant system is considered as a refueller as well as target satellites. By virtue of on-orbit refuelling, the target satellites need not to carry station-keeping propellant. In turn extra payload can be accommodated. However the complete conversion to payload is not possible as mass of bus systems needs to be increased to facilitate for increased payload mass and power. So a conversion factor is added to the following equation that provides the payload mass of a regularly refuelled target satellite. For this study the conversion factor is considered as 0.6.

$$M_p = M_p^* + f M_{sk} \tag{5}$$

where M_p^* is the Payload mass of a target satellite without refuelling, M_{sk} is the Stationkeeping propellant mass and f is the Station keeping propellant to payload mass conversion factor.

The stationkeeping propellant requirement can be calculated by,

$$\begin{aligned} M_{sk} = M_w exp\left(\frac{-\Delta V_{GSO}}{I_{sp} g}\right) \\ \times \left[exp\left(\frac{-\Delta V_S}{I_{sp} g}\right)^{t-1} - exp\left(\frac{-\Delta V_S}{I_{sp} g}\right)^{L^*-1}\right] \end{aligned} \tag{6}$$

where M_w is the wet or liftoff mass of target satellite, ΔV_{GSO} is the Delta-V required from GTO to GSO, ΔV_S is the Per year Delta-V required for station keeping, t is the life corresponding to the residual propellant with target satellite after Station acquisition and L^* is the Life of a target satellite without refuelling.

The primary constraint and the design driver for the refueller are the limit on the maximum lift-off mass that can be obtained by GSLV MKIII launcher. A significant amount of propellant is needed for raising the orbit from geosynchronous transfer orbit to geosynchronous orbit. In order to achieve maximum profitability, the refueller should carry maximum possible propellants to the geo orbit. With the maximum limit on the lift-off mass and requirement to maximise the propellant mass, the dry mass of the refueller need to be optimised. For the study the performance indices used are the Life of the target satellite (L), Unit Telecommunications cost (c) and Relative Profitability (P_{rel}).

A. *Notional Mission scenarios*

As discussed in Section-II-A, based on the strategy used for refuelling run two mission scenarios are analysed for feasibility. ISRO operates different classes of geo satellites from 1000kg class to 4000kg class viz I1k, I2k, I3k, I4k. Based on the selection of mission scenario, L aswell as c and P_{rel} of each category of target satellites in the geo-fleet will change. The operational life, L of each category of target satellites is given by the general equation (7), where the total propellant available in orbit for refuelling is distributed among the target satellites as per their yearly requirement.

$$\begin{aligned} L_i = \frac{\left[\frac{m M_{prop}}{n_i}\right]\left[\frac{M_i n_i}{\sum\limits_{i=1}^{4}(M_i n_i)}\right] - M_{rvd} r_i}{M_i} \; + \; t, \\ i = \{I1k,\; I2k,\; I3k,\; I4k\} \end{aligned} \tag{7}$$

where M_{prop} is Propellant available with each refueller, n_i is the Total number of i_{th} category of target satellite in a fleet (one being I1k), M_i is the Per year propellant requirement for an i_{th} category of target satellite, r_i is the Total number of refuelling interventions for an i_{th} category target and M_{rvd} is the Propellant requirement for rendezvous and docking with a target satellite.

1) Mission scenario - 1: Single Refuelling Run per refueller (SR): Each arriving refueller will visit and refuel all the targets in a single refuelling run and thereby depleting their available propellant. So, Life of target satellites in this scenario can be calculated by substituting r in (7) with number of refueller satellites, m. In this scenario the total propellant used for rendezvous and docking will be less, as there is only one refuelling run per refueller, thus reducing orbit raising and lowering deltaV.

2) Mission scenario - 2: Multiple Refuelling Run per refueller (MR): Due to operational constraints, arranging for refuelling large number of satellites in a fleet will not be possible in all cases. Therefore this scenario considers multiple refuelling runs per refueller with each run three of the target satellites to be serviced. Total RVD propellant used will be more in this scenario due to multiple orbit lowering and raising, thus affecting life of the target satellites. Life of target satellites in this scenario can be obtained by substituting r in (7) with $m\left\lceil \frac{n}{3} \right\rceil$, as three targets are refuelled in each refuelling run.

IV. RESULTS AND DISCUSSIONS

From (1) to (7) it is evident that with cost values kept same, the m, n values and combination of the four categories of satellites in each pair of m and n will dictate the profitability and unit telecommunication cost of target satellite for which life is decided by (7). These performance indices are evaluated for all possible combinations of m and n up to 10 and 25 respectively with four categories to chose from. Thus a total of N_c combinations are studied.

$$N_c = m_{max} \sum_{n=1}^{n_{max}} {}^{4+n-1}C_n$$

$$N_c = 237500 \ for \ m_{max} = 10 \ \& \ n_{max} = 25$$

For instance, a (m, n) pair of 3 refuellers and 7 target satellites will have 120 combinations one of which will be {I1k, I2k, I3k, I3k, I3k, I3k, I4k, I4k}. Studying all combinations will provide a handful of fleet combinations which have desirable values of L, c and P_{rel}. This will provide flexibility while designing fleet for refuelling.

Fig. 1 is showing the density distribution of the life of target satellites for the whole N_c number of combinations. The plot is made with the parameters in Table-III and scenario as SR. Except I1k satellites, all others are having the 15 year life mark inside the interquartile range, thus more probability of having them in a desirable combination. The mean life of heavier satellites (I3k & I4k) are much closer to the required 15 years life with evenly distributed probability near 10 years of life.

A. Selection of desirable combinations

The following constraints are applied on all 237500 combinations to derive combinations with desirable performance indices.

1) The life of the all target satellites in a combination should be between 14 and 21 years.

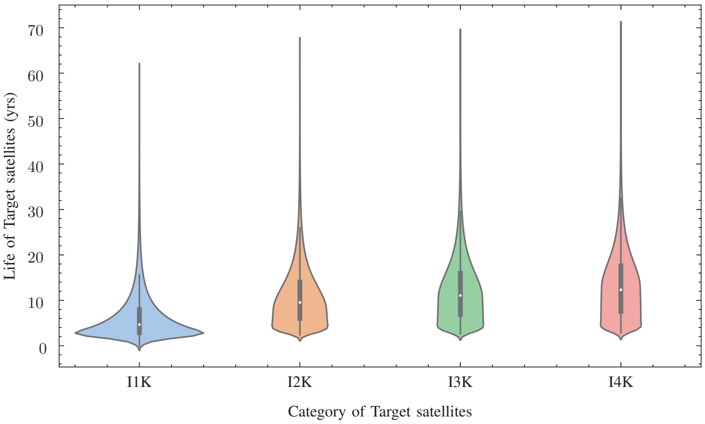


Fig. 1: Distribution of life of different target satellite categories through all combinations ($N_c = 237500$).

As propellant demand for each target satellite is calculated based on their yearly requirement, life of different categories of satellites in a combination will be different. By selecting this range the average life of the satellites in a combination will be close to 15 years, thus providing margin while selecting combinations.

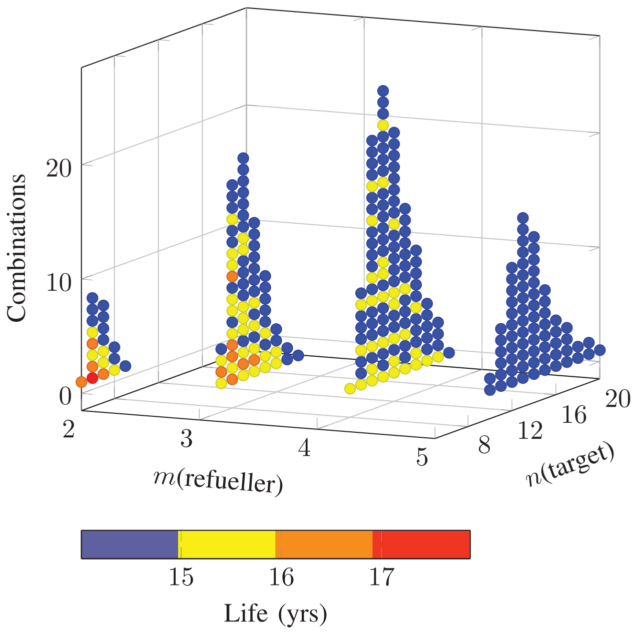
2) The unit telecommunication cost (c) should be less than that of conventional strategy, with out refuelling.
3) The Relative profitability (P_{rel}) should be more than that of conventional strategy, with out refuelling.
4) All four categories of target satellites should be in the combination.

Upon applying the above constraints for SR, the number of combinations is reduced to 278 combinations. Each point in the Fig. 2 & 3 shows a desirable combination of refueller and target satellites. And beyond five refuellers there is no desirable combination with the given constraints. When applying the same constraints to MR, the number of combinations dropped down to 106, still the data shows similar trend. From Fig. 2 & 3 it is evident that with three and four refuellers we get maximum number of desirable combinations for SR. Also, the number of targets with life more than 15 years is increasing with mass of satellite. Thus out of the combinations with three and four refuellers the following combinations are selected from SR and MR scenarios which have life more than 15 years on all categories for further comparison with no refuelling scenario.

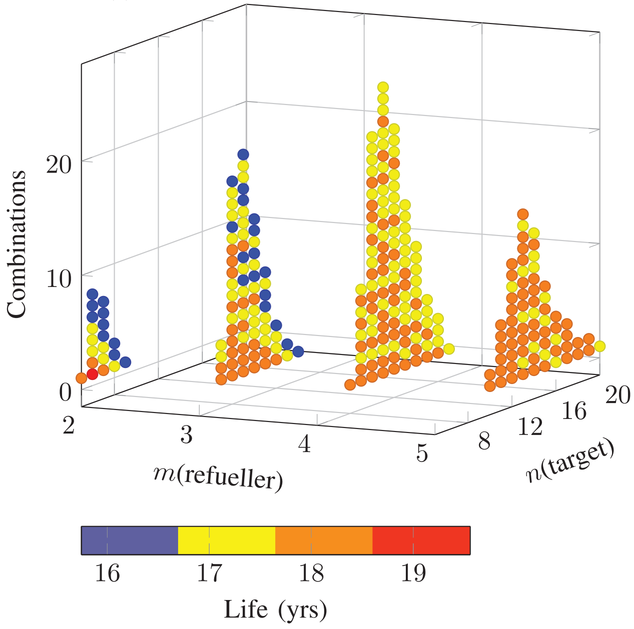
1) Comb-1: 3 Refuellers & 8 Targets.
   a) For SR, {3-I1k, 1-I2k, 2-I3k, 2-I4k}.
   b) For MR, {2-I1k, 2-I2k, 2-I3k, 2-I4k}.
2) Comb-2: 4 Refuellers & 10 Targets.
   a) For SR, {4-I1k, 1-I2k, 1-I3k, 4-I4k}.
   b) For MR, {3-I1k, 2-I2k, 2-I3k, 3-I4k}.

B. Comparison of Refuelling scenarios

Profitability of each class of satellites in Comb-1 and Comb-2 are studied against no refuelling scenario. The operating cost

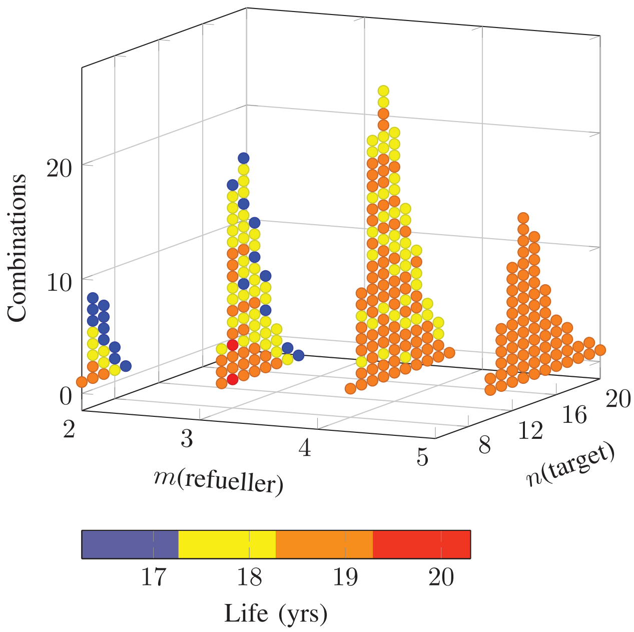


(a) Desirable combinations of I1k satellites

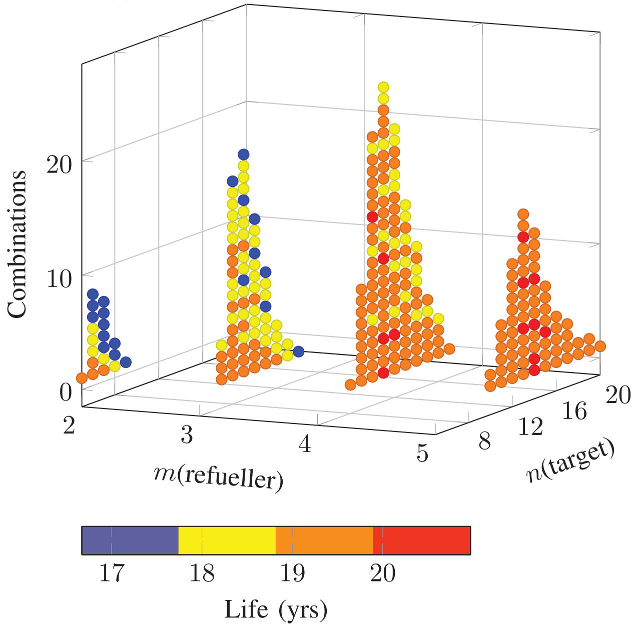


(b) Desirable combinations of I2k satellites

Fig. 2: Desirable combinations of number of refuellers and targets satellites.



(a) Desirable combinations of I3k satellites



(b) Desirable combinations of I4k satellites

Fig. 3: Desirable combinations of number of refuellers and targets satellites.

of all the satellites are considered same. The empirical parameter for launch risk is not considered. Tables I to III shows the parameters considered for each category of target satellites in all scenarios. Delta-V requirement for orbit raising from GTO to GSO is considered as ≈1700m/s for the calculation of beginning of life (BOL) mass of the spacecraft. Dry mass for each weight class is estimated average of the realised satellites. For satellites designed for on-orbit refuelling, propellant is carried only for orbit raising and for the first two years of station keeping operation. This reduces the extra propellant mass and mass of the propulsion system such as tank, as less propellant is loaded. This extra mass is utilised for extra payload. It can be seen from the Table II that with refuelling the payload mass is increased by average of 63% and thus a better usage of the spacecraft bus. It is seen that [Table I & II] with refuelling the satellite cost is higher by 20-25% depending on bus compared to conventional satellite without refuelling. However the revenue obtained due to the increased

TABLE I: Parameters for no Refuelling scenario

Without Refuelling				
	I1k	**I2k**	**I3k**	**I4k**
Liftoff mass (kg)	1425	2550	3500	4500
Drymass (kg)	625	1100	1500	1930
Payload mass (kg)	110	250	380	490
BOL mass (kg)	821.7	1472.6	2022.4	2601
Satellite cost (cr)	125	200	300	400
Launch cost (cr)	150	250	400	450
Life (yrs)	10	12	15	15

TABLE II: Parameters for Refuelling scenario for $f = 0.6$

With Refuelling				
	I1k	**I2k**	**I3k**	**I4k**
Liftoff mass (kg)	1425	2550	3500	4500
Drymass (kg)	798.7	1411.4	1927.7	2480
Payload mass (kg)	173.95	394.41	636.6	820
BOL mass (kg)	821.7	1472.6	2022.4	2601
Satellite cost (cr)	156.3	250	375	500
Launch cost (cr)	150	250	400	450

payload mass and life of the target satellite will be higher. Here the lift-off mass of the refueller is kept constant and dry-mass is considered as minimum as possible. So the BOL mass of the refueller can be considered a constant for the initial study. Thus the amount of propellant used for refuelling (M_{prop}) can also be considered as a constant.

It is not desirable to keep the refueller operational for long to reduce the maintenance cost. So it is advisable to refuel as many satellites as possible thus distributing the refueller maintenance cost to more satellites. This will reduce the overall cost. The graph shown in Fig. 4 compares the unit telecommunication cost of different scenarios against no refuelling scenario. It is evident from the graph that for all scenarios c is reduced by an average of 33%. Also, the c for all refuelling scenarios shows similar values as the increase in number of refuellers is compensated by the increase in number of target satellites.

The payload advantage (ΔM_p) got is by partially swapping station keeping propellant with payload. Therefore a mere increase in life of the refuelled satellite will not be sufficient to achieve desirable profitability even though the profitability and relative profitability is increasing with BOL mass of satellite (Fig. 5). So, the refuelled satellite must accommodate the extra payload capability it got by virtue of refuelling with revenue generating payloads to reduce the unit telecommunication cost. In practice an increased satellite life can be achieved thus reducing the cost even more.

Upon comparing the relative profitability of both the combinations (Comb-1, Comb-2) in mission scenarios SR and MR, Comb-1 in scenario SR is having more relative profitability compared to other scenarios. This is due to the less number of refuellers in Comb-1 and more life as less target satellites are refuelled and that too in single refuelling run, ie SR. But as the mass of target satellites increases, the relative advantage between each scenario is reducing as more and more payload is accommodated in heavier satellites. The life of the target satellites in each scenarios discussed is in a range of 14 years to 21 years with life increasing by BOL mass, thus providing adequate margin for selection of each combination.

TABLE III: Fuel requirements considered for feasibility study, m_{rvd} & M_{prop} is considered same for all categories as they depend on refueller.

	I1k	I2k	I3k	I4k
M_{prop}	1400	1400	1400	1400
M_i	13	23	30	40
M_{rvd}	25	25	25	25

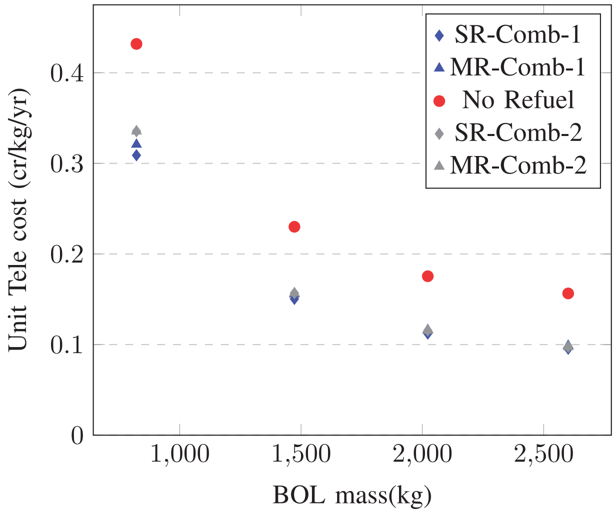


Fig. 4: Unit telecommunication cost of different scenarios, compared to no refuelling scenario, with $f = 0.6$

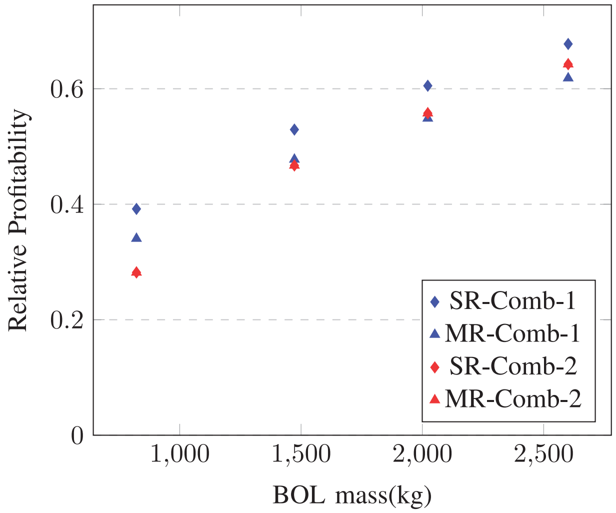


Fig. 5: Relative profitability of different scenarios compared, with $f = 0.6$

C. Impact of conversion factor (f)

With conventional cuboid satellite configuration, as the satellite mass is increased, the payload content is also increased. However, the overall volume is not optimally used resulting in reduced packing efficiency. This is because the payload is accommodated on the surfaces of the cuboid, rather than in the bulk volume. Currently this is being mitigated by using intermediate decks in satellite structures. Yet the packing efficiency is lower. This is mainly due to issues related to accommodation and thermal control. With refuelling, a smaller propellant tank is accommodated, thus allowing to increase the number of intermediate decks. So, for heavier satellites the conversion factor (f) can be assumed to be more. The following equation can be employed for evaluating f.

$$f = 1 - exp(-k * M_p^*) \tag{8}$$

where k is the growth coefficient, which can be tuned as the configuration of target satellites matures. Fig. 6 shows the variation of c/P_{rel} with respect to satellite mass, calculated by (8) for $k = 0.006$. It can be seen from the Fig. 6 that heavier satellites have desirable values of c and P_{rel}.

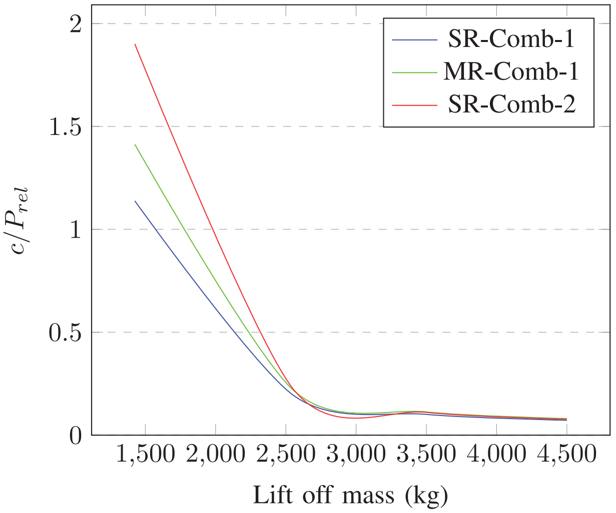


Fig. 6: c/P_{rel} for different scenarios with $k = 0.006$

V. CONCLUSIONS

In the above cost modelling studies, it is evident that the main parameters that affect the profitability of the system are refueller satellite dry mass, payload mass of the target satellites, number of satellites refuelled and number of refuelling runs.

The study thus verifies that the revenue obtained by the increase of payload content and life of the target satellites will be more than the cost to launch and operate refueller satellites and cost to operate the target satellites for the extended life. The following inferences were made assuming the refueller satellites are operational for two years.

1) It is more probable for I3k & I4k satellites in a combination to have life close to 15 years whereas I1k & I2k satellites will have life close to 10 years. So, while designing a refuelled fleet it is preferable to select the above mentioned life values for target satellites.
2) Ratio of dry mass to lift off mass of target satellites should be greater than 0.5.
3) Out of the two notional scenarios studied viz. SR & MR with various combinations, Comb-1 in SR shows better profitability.
4) It is seen that an average increase of 58% in payload mass for I1k & I2k satellites and 67% for I3k & I4k satellites can be obtained by refuelling in-orbit for a station keeping fuel mass to payload mass conversion factor (f) of 0.6.

The increase in payload mass due to refuelling must be used to increase the payload content, thus increasing overall revenue. As mere increase in life of satellites won't provide a desirable profitability, the target satellites are to be specifically designed considering refuelling in mind. Thus refuelling will pave way for high density satellites.

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